ABSTRACT
Obstacles, such as buildings and trees, interfere with radio wave signal propagation by contributing fading and shadowing effects. To produce results that accurately reflect real-world topologies, models must address the radio-interfering conditions that obstacles present. Failing to account for the effects of obstacles can therefore inaccurately overstate network performance. An obstacle shadowing model was implemented for the ns-3 network simulation toolset and tested using an ns-3 script for wireless vehicular ad hoc network (VANET) scenarios and obstacle data from Open Street Map (OSM). Results show that deterministic obstacle shadowing compares differently than stochastic Nakagami-m fading. The obstacle shadowing model algorithm can be executed in time complexity similar to other simpler models. Including realistic obstacle shadowing in simulation modeling improves performance assessment.

Categories and Subject Descriptors

General Terms

Keywords
Obstacles, propagation loss, fading, shadowing, simulation, ns-3.

1. INTRODUCTION
Outdoor obstacles, such as buildings, buses, and trees, challenge network researchers to produce accurate and consistent results [1] because obstacles interfere with radio signal propagation by contributing fading and shadowing effects, especially in a vehicular ad hoc network (VANET) [2]. To improve simulation results, models must accurately reflect the real-world topology and their impact to the energy of signals traveling through it. While deterministic radio wave attenuation models are often supplemented with stochastic models that reflect fading effects, the stochastic nature of such intended model improvements determine the physical parameters of channel transmissions in a completely probabilistic manner without considering underlying geometry [3] and could therefore deviate severely from realistic behavior, negatively impacting performance assessments [4].

This research presents an accurate, deterministic obstacle shadowing model for ns-3 [5] that follows the empirically-validated model introduced in [4] and discusses how it impacts network performance assessment. The following research questions (RQ) guide our investigations:

RQ1: Can fast fading and shadowing effects of obstacles, such as buildings, vehicles and trees, be modeled and efficiently simulated in ns-3?

Because model realism improves simulation results, a deterministically real fast fading and shadowing model that accounts for radio wave propagation through obstacles will improve the usefulness of existing detailed network simulation tools, such as ns-3.

RQ2: How does performance in a VANET compare between the deterministic obstacle shadowing model and other stochastic fading and shadowing models?

By implementing a deterministic obstacle shadowing model and quantifiably comparing simulation results to other stochastic fading models, a performance characterization of the obstacle shadowing model can be made.

Our primary contributions include:
1) Following the existing, validated model introduced in [4], an efficient implementation of an obstacle model based on computational geometry techniques was developed and offered to the ns-3 network simulator community.

2) Simulation results using obstacles compare quantitatively the effects of i) deterministic obstacle shadowing to ii) stochastic Nakagami-m fast fading and iii) no fading.

This paper is organized as follows: Section 2 provides background information and discusses related work and Section 3 describes the obstacle shadowing model. Section 4 describes the experimental setup, results and analysis. Section 5 concludes the paper and Section 6 discusses future work.

2. BACKGROUND AND RELATED WORK
2.1 DSRC
To improve driving safety and reduce traffic-related fatalities, regulations will require vehicles to communicate cooperatively using wireless technologies [6], thereby enabling both safety applications, such as accident avoidance, and non-safety
applications, such as traffic congestion alerts [7]. The most promising technologies that will enable such a VANET are collectively referred to as Dedicated Short Range Communications (DSRC). DSRC-related standards include IEEE Std. 802.11-2012, IEEE Std. 1609 / Wireless Access for Vehicular Environments (WAVE), and SAE J2735 Message Set Dictionary. Figure 1 shows the DSRC reference model.

<table>
<thead>
<tr>
<th>Application</th>
<th>DSRC Message Set Dictionary SAE J2735</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>TCP 1609.3 IPv6 WSM 1609.3</td>
</tr>
<tr>
<td>Internet</td>
<td>Management LLC 802.2 MAC 802.11 1609.4</td>
</tr>
<tr>
<td>Data Link</td>
<td>Security 1609.2</td>
</tr>
<tr>
<td>Physical</td>
<td>PHY 802.11 (p)</td>
</tr>
</tbody>
</table>

Figure 1: Reference model for DSRC technologies used by vehicular ad hoc networks.

IEEE Std 802.11-2012 incorporates modifications to the media access control (MAC) and PHY layers (formerly known as IEEE 802.11p) intended to address the dynamic nature of potentially fast-moving vehicles. A primary enhancement allows a station that is not a member of a Basic Service Set (BSS) to transmit data frames, allowing the PHY to operate “outside the context of a BSS,” (i.e., OCB) and thus defining a new type of 802.11 communications. DSRC achieves data rates from 3 to 27 Mbps [8], although the majority of testing in the U.S. utilizes the 6 Mbps configuration (i.e., Quadrature Phase Shift Keying, QPSK, with rate 1/2 coding) [9].

The IEEE Std 802.11 supports safety beacons via broadcast transmissions (i.e., beaconcasting) that present challenges to calculating common network performance metrics, such as Packet Delivery Ratio (PDR), because such broadcasts are unacknowledged and receipt by other nearby vehicles is not guaranteed.

By sensing the network and delaying transmissions when it is found busy, Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) avoids but does not entirely prevent transmissions that could otherwise cause a collision, especially in the hidden node scenario [10] in which vehicles are unaware that their imminent transmissions would collide with those of other nearby vehicles.

IEEE Std. 1609/WAVE provides further capabilities, such as: channel allocation and multi-channel access, priority queueing and channel routing, congestion control, security and privacy mechanisms, and an application programming interface (API) for messaging. WAVE supports IPv6-based data transfers and also non-IP-based traffic through the WAVE Short Message Protocol (WSMP). The design of IEEE 1609/WAVE supports a single control channel (CCH) and six service channels (SCH) that are defined in the 5.9 GHz range and typically occupy 10 MHz each. It is generally assumed that the CCH will be mostly dedicated to safety applications [8], with non-safety data and Internet Protocol (IP) traffic destined for the SCH. Sync intervals split the channel at a rate of 10 Hz, which CCH and SCH intervals then split equally, with a 4ms guard interval separating channel switches. Continuous channel access is also supported.

The WAVE standard addresses message priority using four different Access Classes (AC) per (CCH or SCH) channel, AC0 (lowest priority) to AC3 (highest priority), with the MAC layer maintaining separate queues and channel access for each AC [8]. The WAVE contention mechanism is similar to the one used in conventional Wireless Local Area Network (WLAN) and the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) Quality of Service (QoS) enhancements [11].

Using the SAE J2735 DSRC Message Set Dictionary [12], the VANET applications are developed over the 1609/WAVE stack. Data elements that enable many safety applications are described in the most important message in the J2735 standard [8], the Basic Safety Message (BSM), which every vehicle has to broadcast at a nominal rate of 10 Hz. The BSM is divided into:

i) Part I mandatory elements, e.g., position, motion, braking status, and vehicle size and
ii) Part II optional elements, e.g., vehicle events, path history and path prediction.

Additionally, SAE J2735 provides guidelines on message prioritization among different message types. Applications may involve strictly vehicle-to-vehicle (V2V) messaging using an On-Board Unit (OBU), or may also involve the use of a Roadside Unit (RSU) to support vehicle-to-infrastructure (V2I) communications. The Federal Communications Commission (FCC) defines four classes for DSRC device operations with desired communications zones ranging from 15 to 1000 meters with typical operation expected in the 400m range [8]. While vehicles and infrastructure expect to communicate reliably over these ranges, radio-blocking obstacles and other interference that prevent message delivery challenge the effectiveness of all safety applications.

2.2 Radio Propagation Models

A Radio Propagation Model (RPM) handles the effects of signal attenuation due to distance, multipath signal fading due to reflectors, and shadowing as radio waves move through free space and obstacles, such as buildings. Accurate environmental representation of obstacles is absolutely required in urban scenarios to benefit VANET simulation [2]. Radio wave attenuation is often modeled deterministically based mainly on inter-vehicular line-of-sight (LOS) distance, while some modelers improve upon this with stochastic modeling intended to account for radio wave shadowing.

Many different RPMs have been proposed for VANET, ranging in their design complexity from simpler models such as unit-disk up through more complex ones that specifically address the interference that obstacles cause. The simplest model, often used in VANET simulation, is the unit-disk model, in which vehicles can communicate with each other if they are within a threshold distance and cannot communicate otherwise [3]. Another commonly simulated RPM in VANET is the two-ray model, which takes into account signal reflection from the road surface to represent path loss in inter-vehicle communications (IVC) [13]. For (small-scale) fast fading models, various stochastic distributions have been proposed, including Rice, Rayleigh,
Nakagami-m, lognormal and Weibull distributions [3]. Because stochastic models do not consider underlying geometry [3], they could deviate severely from realistic behavior, negatively impacting simulations of transmission-critical safety applications [4]. A special case of the general gamma distribution, the Nakagami-m fading model determines signal power reception probabilistically dependent on model parameters that simulate fading levels and can be described as:

\[
I_{\text{Nakagami-m}}(r; m, \Omega) = \frac{m^m}{\Theta(m)} \frac{r^m}{\Gamma(m)} e^{-\frac{m}{2} \frac{r^2}{\Omega}},
\]

where \( m \) is the Nakagami parameter (i.e., shape parameter), \( \Theta(m) \) is the gamma function, and \( \Omega \) is the average power of multipath scatter field, which controls the distribution spread.

### 2.3 Obstacle Modeling

Modeling improves when a visibility scheme describes the topology as a configuration space and supports obstacle detection. Most visibility schemes divide the configuration space into sub-areas by some criteria. For example, although uncommon in real scenarios [14], the Manhattan grid model assumes that all vehicles move only in streets arranged as a Manhattan-style grid and treats non-street areas as buildings. Current approaches to detect obstacles within a configuration space [14] [1] [15] employ different algorithms with varying complexity. Many come from computational geometry techniques including intersection problems [16] [4] and binary space partitions (BSP) [4] that are applied to model vehicles and/or buildings as obstacles.

Models that fail to consider realistic road topologies and the presence of obstacles [1] lead to inconsistent results [17]. Especially in certain simulation scenarios, such as VANET, accurate environmental representation of obstacles is absolutely required in urban scenarios because obstacles not only constrain vehicular movement but also interfere with radio transmissions [2]. Signal propagation varies especially between LOS and obstructed-line-of-sight (OLOS) [18] and when radio waves propagate “Around-the-Corner” (ATC) [4].

Radio wave attenuation is often modeled deterministically based mainly on inter-vehicular LOS distance, while stochastic modeling improves upon this by accounting for radio wave shadowing. Recent research deterministically models shadowing by addressing radio wave propagation through buildings [4] [1] [19].

### 2.4 Performance Assessment and Metrics

Network level metrics have been historically important to the understanding and tuning of traditional Internet and Mobile Ad hoc Networking (MANET) communities [20]. Performance measurements considered are often network- (or packet-) level metrics (e.g., PDR and Average Per-Packet Latency). For example, PDR is the percentage of broadcast packets that are successfully received by all vehicles within each transmitting vehicle’s coverage range, \( d \) [20] [21]. Reception failures degrade PDR due to concurrent transmissions, hidden terminal problems and channel fading [21].

Being a physical phenomenon, the impact of radio-blocking obstacles in VANET scenarios can extend contrastingly beyond network-level measures and thus into all layers in the protocol stack reference. In VANET assessment, performance of intended safety-based applications carries the most importance. Instead of network-level performance, VANET application performance depends on reliability metrics (e.g., Application-level T-Wind Reliability, awareness probability, and awareness range) [20] [22] [21] that are difficult to assess. For example, awareness probability is the probability of receiving at least \( n \) packets in the tolerance time window, \( T_{tol} \) [21] [22]. Whereas PDR describes the wireless communication reliability at the packet level, awareness probability describes the application-level reliability for safety applications [20]. By assessing communications reliability, such metrics are more suitable for measuring VANET safety performance.

### 3. OBSTACLE SHADOWING MODEL

#### 3.1 Obstacle Model

Vehicles that would likely receive one another’s transmissions in unobstructed conditions may instead need to account for the effects of radio waves as they travel through obstacles. To deterministically evaluate for ns-3 the effects of obstacles, an obstacle model is implemented in which two-dimensional polygons represent obstacle boundaries. Figure 2 shows an example urban downtown scenario (Raleigh, NC USA) using buildings data from OpenStreetMap (OSM) [23] and simulated in the open source traffic simulation package Simulator for Urban Mobility (SUMO) [24] [25]. As can be seen in the example, the OLOS between two vehicles may pass at oblique angles through multiple walls and interior distances among several buildings.

Using the obstacle model, an obstacle-aware shadowing model leverages the Computational Geometry Algorithms Library (CGAL) to count the number of walls as obstacle intersections, calculate the distance traveled through obstacles as interior intersection lengths and implement deterministically the shadowing effects of wireless transmissions for OLOS pathways.

To implement the model, propagation and core modules of the ns-3 reference model were enhanced, as shown and identified in Figure 3.

Three classes comprise the obstacle model: Obstacle retains the geometric elements to represent an obstacle, Topology uses it to load obstacle data points into a managed collection, and ObstacleShadowingPropagationLossModel uses both to implement the obstacle shadowing propagation loss model. All classes are initially placed in a new ns-3 module, `obstacle`.

The Obstacle class represents an obstacle using a CGAL Polygon_2 object, and retains parameters that determine the fading effects through obstacle walls and interior space.
The **Topology** class loads buildings data from a file in the format as available through OSM [23] and processed using SUMO’s Polyconvert utility. For real-world settings, a user obtains from OSM the buildings data file for the region of interest (e.g., a city area) by selecting, for example, a rectangular area and downloading from OSM the XML-like data from which buildings footprint details are extracted. Next the user processes the results with Polyconvert, producing the resulting buildings data file that defines shapes as point-defined polygons and loads it into the **Topology** object via the LoadBuildings() method. A subset from an example buildings file is shown in Figure 4. A similar process may be followed for synthetic scenarios by creating a file of `<poly shape>`-defined buildings of desired dimensions. A single topology instance to handle all buildings is assumed. Furthermore, the **Topology** object can be used to determine the obstructed loss between two points by use of the GetObstructedLossBetween() method, which implements the algorithm that determines for two vehicles (i.e., points) the number of walls penetrated and total distance traveled through obstacles, for which the pseudo-code is given in Figure 6.

When considering obstructions between two vehicles, only obstacles that lie less than 500m between the vehicles are included, as obstacles at greater distances tend to entirely block residual radio wave energy. Figure 5 further illustrates an example where two vehicles (i.e., V1 and V2) are shown with the OLOS between them as a dashed line. Shaded around each vehicle is a circle of 500m radius that represents the region of potential obstructing obstacles (i.e., corresponding to step 4 is the algorithm of Figure 6). For performance optimizations, potential obstacles are found by searching a BSP of obstacle centerpoints (i.e., the midpoint of an obstacle’s bounding box). An example centerpoint, P, is labeled in Figure 5, within the region surrounding vehicle V1. All buildings with centerpoints within the shaded regions are each tested for intersections along the OLOS path between the two vehicles. For each obstacle that meets the intersection test, the total number of intersection edges (i.e., walls) and distances within the obstacle interiors are determined and the ensuing sum total is returned. As an additional optimization, inter-vehicle obstacle obstructions are cached by assuming that each pair of vehicles that have not both changed position by more than 0.1m retain the same obstructed-distance results.

### Figure 3: Obstacle shadowing model enhancements to the ns-3 reference model (from [5])

<table>
<thead>
<tr>
<th>ns-3 Source Code Modules</th>
<th>Existing Usage and Examples</th>
<th>Extensions for Obstacle Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>test</td>
<td>High-level wrappers for everything else aimed at scripting</td>
<td>obstacle shadowing propagation loss</td>
</tr>
<tr>
<td>protocol</td>
<td>Fis, Two-Ray Ground, Nakagami-m loss</td>
<td></td>
</tr>
<tr>
<td>mobility</td>
<td>Mobility modules (static, random walk, etc.)</td>
<td></td>
</tr>
<tr>
<td>network</td>
<td>Packets, Packet tags, Packet headers, Node class, NetDevice, Address types (IPv4, MAC, etc.), Queues, Sockets</td>
<td></td>
</tr>
<tr>
<td>core</td>
<td>Smart pointers, Dynamic type system, Attributes, Callbacks, Tracing, Logging, Random variables, Events, Schedulers, Time arithmetic</td>
<td>obstacles, topology management</td>
</tr>
</tbody>
</table>

### Figure 4: A subset of buildings data extracted from OpenStreetMap (e.g., for the downtown Raleigh, NC USA area) and processed using SUMO’s PolyConvert, showing building footprint dimensions, in meters, as polygonal areas defined by their point sets.

### Figure 5: Radio-wave-blocking obstacles are potentially in range based upon the distances between each vehicle and an obstacle’s centerpoint (e.g., as shown by P)

#### 3.2 Propagation Loss

In ns-3, the generic interface PropagationLossModel serves as the base class from which many propagation loss models have been implemented [5]. For example, the Nakagami-m loss model in ns-3 implements the stochastic fading process of (1) that suitably captures the fast-fading effects in obstacle-laden VANET scenarios [3], leveraging the fact that the Nakagami-m distribution is a special case of the gamma distribution. Furthermore, the ns-3 propagation loss interface supports loss-chaining, allowing researchers to concatenate the loss effects of multiple models. Thus, a user could set up a simulation to use the Two-Ray Ground or Friis propagation loss model, and additionally chain Nakagami-m fading and/or other supported models.
propagation loss models to evaluate additional fading and/or shadowing effects.

Following the validated model introduced in [4], an obstacle shadowing model was developed for the ns-3 network simulation toolset using computational geometry techniques to determine OLOS distances traversed and number of segment intersections (i.e., walls penetrated) in roadway scenarios using building footprint information from OSM.

Slow fading shadowing effects of obstacles are modeled using the existing, empirically-validated Simple Obstacle model of [4], in which obstacle shadowing path loss, \( L_{S,O} \), is dependent on both per-wall-attenuation and per-meter-attenuation as:

\[
L_{S,O} = \alpha n + \beta d_o, \tag{2}
\]

where \( \alpha \) is the attenuation per wall, in decibels (dB), \( n \) is the number of walls penetrated, \( \beta \) is the attenuation per meter, in dB, and \( d_o \) is the distance, in meters, traveled through obstacles. Default values as per [4] of \( \alpha = 9 \) dBm and \( \beta = 0.9 \) dB / m are used. However, the ns-3 implementation supports configuration of these values per obstacle, so that radio wave propagation effects can be modeled for obstacles composed of different types of construction materials (e.g., “brick and mortar” buildings versus houses, garages, sheds, etc.).

For every obstacle \( o \in O \), do:
6. if the distance from \( p_1 \) or \( p_2 \) to the obstacle center is within range, \( r \), then
7. for each edge \( s \in o \),
8. if \( s \) intersects a ray from \( p_1 \) to \( p_2 \),
9. \( n \leftarrow n + 1 \) (i.e., found an obstructing wall)
10. save the min. and max. distances from \( [p_1, p_2] \) to the intersection pt. (i.e., to find spanning interior distance among the edges of \( o \))
11. \( m_o \leftarrow m_o + \) distance between min., max. values in step 10 (i.e., spanning interior obstructed distance)
12. return \( m_o \) and \( n \)

Figure 6: Pseudo-code for the algorithm that determines the number of obstacle wall intersections and obstructed distance between two points

As an example calculation, consider a scenario (e.g., as in Figure 2) where the line between two vehicles passes through \( n=6 \) walls and an interior distance of \( d_i = 32m \). Substituting into (2) yields \( L_{S,O} = 6 \times 10 + 0.9 \times 32 = 88.8 \) dB. With the cumulative losses for this example, it is unlikely that a transmission from one vehicle would have sufficient power to be received by the other, as obstacle shadowing causes significant propagation loss.

To implement the model, class ObstacleShadowingPropagationLossModel derives from PropagationLossModel and can thus be used in ns-3 for propagation loss chaining so that researchers can evaluate the loss effects of various models by potentially concatenating them together. For example, a user could additionally chain the obstacle shadowing model to other supported propagation loss models (e.g., Two-Ray Ground, Friis, and Nakagami-m) to evaluate additional fading and/or shadowing effects.

4. EXPERIMENTAL SETUP AND RESULTS
4.1 Experimental Setup
Several steps are necessary to set up an experiment that uses the obstacle shadowing model, as shown in Figure 7. First, buildings data is obtained from OSM and fed through SUMO’s Polycover utility and also optionally included in SUMO’s Netconvert utility if obstacles are to be shown in SUMO’s vehicular simulation. Next, SUMO combines road network and simulation criteria to produce a vehicular trace file that is converted to ns-2 format using the traceExporter2.py python script. Lastly, the buildings data is loaded into ns-3 (i.e., via the Topology class) and the ns-2 vehicle trace file is played back using Ns2MobilityHelper while the network configuration is simulated.

To answer RQ1 the obstacle shadowing model was implemented for the ns-3 network simulation toolset and to answer RQ2 it was tested using the (ns-3 wave) vanet-routing-compare script that enabled BSM traffic only (i.e., disabled routing protocol traffic) and was extended to support scenarios with obstacles.

Figure 7: Process flow for experimental setup: extracting buildings data from OpenStreetMap, vehicular modeling in SUMO, and network simulation in ns-3

To test the obstacle shadowing model, scenarios with numerous interestingly-shaped buildings were sought in which many nodes would generate wireless traffic frequently and by movement would change their orientation among the set of buildings. Shadowing effects vary among different topological environments as building density varies, requiring deterministically different evaluations of each scenario. Wireless VANET scenarios in open...
highway, residential neighborhood, and urban downtown settings were ultimately selected, with topology parameters as shown in Table 1.

Table 1: Scenario topology parameters

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Open highway</th>
<th>Residential neighborhood</th>
<th>Urban downtown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>N</td>
<td>35.8855</td>
<td>35.8758</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>35.8420</td>
<td>35.8650</td>
</tr>
<tr>
<td>Longitude</td>
<td>W</td>
<td>-78.8858</td>
<td>-78.6770</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>-78.7785</td>
<td>-78.6502</td>
</tr>
<tr>
<td>Approx. Area (sq. mi.)</td>
<td></td>
<td>39.17</td>
<td>1.68</td>
</tr>
<tr>
<td>Buildings</td>
<td></td>
<td>348</td>
<td>1440</td>
</tr>
<tr>
<td>Traffic lights</td>
<td></td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Vehicles, routes</td>
<td></td>
<td>50-250</td>
<td>50-250</td>
</tr>
<tr>
<td>Car-following model</td>
<td>Krauss</td>
<td>Krauss</td>
<td>Krauss</td>
</tr>
</tbody>
</table>

Network simulation uses the mobility trace files produced by SUMO simulations (i.e., ns-2 trace files) played back for 2000 seconds (i.e., 33.3 minutes) of network simulation time in ns-3 during which every vehicle emits a BSM 10 times per second. Network simulation parameters are summarized in Table 2 with example command line arguments for the vanet-routing-compare script that users can modify to evaluate different VANET simulation scenarios. Propagation loss is calculated for each transmission between sender and other nearby potential receiving vehicles.

Table 2: Network simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>ns-3 command line argument</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSM size</td>
<td>200 bytes</td>
<td>--bsm=200</td>
</tr>
<tr>
<td>BSM rate</td>
<td>10 Hz</td>
<td>--interval=0.1</td>
</tr>
<tr>
<td>Transmit power</td>
<td>20 dBm</td>
<td>--tx=20</td>
</tr>
<tr>
<td>Frequency</td>
<td>5.9 GHz</td>
<td>(N/A - value hard-coded)</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>10 MHz</td>
<td>--phyMode=OfdmRate6MbpsBW10MHz</td>
</tr>
<tr>
<td>Channel access</td>
<td>802.11p OB</td>
<td>--80211Mode=1</td>
</tr>
<tr>
<td>Tx range</td>
<td>50 - 2000 m</td>
<td>--txdist[n]=1[d]</td>
</tr>
<tr>
<td>Sync. time accuracy</td>
<td>1-10 as uniform</td>
<td>--sptacuracies=1-10</td>
</tr>
<tr>
<td>Encoding</td>
<td>OFDM</td>
<td>--phyMode=OFdmRate6MbpsBW10MHz</td>
</tr>
<tr>
<td>Rate</td>
<td>6 Mbps</td>
<td>--phyMode=OFdmRate6MbpsBW10MHz</td>
</tr>
<tr>
<td>Propagation loss model</td>
<td>Two-ray ground</td>
<td>--lossModel=3</td>
</tr>
<tr>
<td>Simulation time</td>
<td>2000 s</td>
<td>--totaltime=2000</td>
</tr>
<tr>
<td>Fading Model</td>
<td>Obstacle Shadowing</td>
<td>--buildings=1</td>
</tr>
</tbody>
</table>

To compare the effects of obstacle shadowing, identical experiments are repeated and results compared using different propagation loss models for:

i) two-ray ground propagation loss only,
ii) two-ray ground propagation loss and stochastic Nakagami-m fast fading, and
iii) two-ray ground propagation loss and deterministic obstacle shadowing.

Performance is evaluated by comparing the PDR (i.e., the ratio of actually received packets to expected packets) among different path loss models for a given coverage radius from the transmitter.

4.2 Results and Discussion

Using ns-3, simulations evaluate path loss between vehicles using the two-ray ground propagation loss model, with additional fast fading effects modeled using the obstacle shadowing model of this research and compared to the stochastic Nakagami-m fading model as well as results without any fading effects.

The varying effects of propagation loss models can be explained by example of a downtown intersection, as shown in Figure 8. Here, traffic signaling causes vehicles to gather often at intersections. When obstacle shadowing is ignored, the propagation loss effects of the buildings is unaccounted for between vehicles V1 and V2 and also V1 and V3, leading to an overstatement of the likelihood of packet reception. However, if stochastic fading models are used, then the fading potentials between vehicles V2 and V3 are equally probable as between V1 and V2 or V1 and V3; resulting in an understatement of the communications potential between the unobstructed vehicles V2 and V3.

The increased path loss from fading effects decreases PDR, as does increased shadowing path loss from higher obstacle density. Figure 9 compares the PDR at a range of 500m over time for an urban downtown scenario with 250 vehicles for the different propagation loss models. Earlier results (e.g., prior to 500s) show more variability before the randomization of vehicle trip and traffic light signaling leads to more steady-state behavior of vehicle flows. The PDR for “no fading” is the highest, as no additional fading and shadowing losses are taken into account. Repeating the same scenario and including stochastic Nakagami-m fading effects results in the lowest PDR, as additional fading is probabilistically considered for every vehicle transmission potential. Results for obstacle shadowing lie between the “no fading” and stochastic fading results, implying that a deterministic evaluation of obstacle shadowing shows a fading effect that is not as severe as evaluating propagation loss stochastically for every transmission, as achieved using Nakagami-m fading.

Lastly, the PDR average and standard deviation (i.e., 1-σ) are shown in Table 3. For the same scenario repeated with only changing the fading model, obstacle shadowing shows the least variation over time.

The results of Table 3 are explained by the obstacle shadowing effects in scenarios with high obstacle densities tending to bifurcate results into those that are entirely unobstructed and so allow successful delivery and those that encounter sufficient radio wave blockage that prevents delivery. In effect, obstacles increase spatial reuse. Similar to the effects experienced by party
guests that relocate to more quiet places to continue conversation, often placing walls between themselves and other, louder side-conversations, so too do obstacles such as buildings block inter-vehicle communications thus improving localized PDR, an effect that we call The Dinner Party Effect. However, while obstacle shadowing can therefore improve PDR, there is also a downside in that messages that are prevented from reaching recipients could jeopardize safety.

4.3 Performance
Scenarios were simulated for 30 trials each with 50-750 vehicles moving in highway, residential, or downtown areas via ns-2 trace files and each node transmitting 10 BSMs per second, for 2000s of simulation time. Each trial was repeated to evaluate three different fading models: no fading, stochastic Nakagami-m fading, and deterministic obstacle shadowing. Simulations were conducted using the equipment from the High Performance Computing (HPC) services at North Carolina State University, with the longest scenario taking up to six wall-clock days to complete. As shown in Figure 10, although the average times indicate that the expected overhead of using the deterministic obstacle shadowing model is greater than the stochastic Nakagami-m fading model, the confidence intervals imply that the simulation performance of the obstacle shadowing model in on the time complexity order of using the Nakagami-m fading model.

5. CONCLUSIONS
Performance assessments improve when models accurately reflect environmental conditions such as the fading effects of radio wave propagation through buildings and other obstacles. Results based on stochastic Nakagami-m fading fail to realistically differentiate between highway, residential, and urban settings and differ from the deterministic results obtained using the obstacle shadowing model.

An obstacle model and a fading model that uses it has been implemented and offered to the open source ns-3 network simulator community. The models are shown to execute efficiently with simulation overhead on the time complexity order of the stochastic Nakagami-m fading model. Results generated from simulation experiments that use these models show that deterministic obstacle shadowing can greatly degrade PDR and compares differently than stochastic Nakagami-m fading. Failing to account for the effects of obstacles can therefore inaccurately or even greatly overstate the performance of VANET scenarios. Including realistic obstacle shadowing in VANET simulation modeling improves VANET assessment.

### Table 3: PDR average and standard deviation for three fading models

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fading</td>
<td>14.38%</td>
<td>2.48%</td>
</tr>
<tr>
<td>Nakagami-m fading</td>
<td>5.60%</td>
<td>1.33%</td>
</tr>
<tr>
<td>Obstacle Shadowing</td>
<td>10.85%</td>
<td>0.56%</td>
</tr>
</tbody>
</table>

6. FUTURE WORK
Although our obstacle shadowing model for ns-3 and tested by simulating an IEEE 802.11-enabled VANET shows that the influence of obstacle shadowing can significantly influence performance, additional actions can be pursued to further enhance and test the model.

First, while the obstacle shadowing model implemented in ns-3 follows the empirically-validated model of [4], it remains unclear if this is, in fact, the best model for obstacle shadowing, even in VANET scenarios. Thus, additional modeling and validation may further improve the model. For example, a small but real-world scenario with known or expected inter-point losses could be studied to better understand and validate the combining effects of path loss, fading, and/or shadowing models in ns-3 simulations. Furthermore, the model as implemented by (2) takes into account signal attenuation due to obstacles but does not demonstrate that signal reflections can be ignored. Additionally, the current model current uses fixed values for loss per wall and interior distances, whereas real-world measures may find these values to instead be random values or perhaps vary by building type, size, or construction materials. A source of information for building composition densities and radio absorption properties would helpfully enhance this venture.

Second, the current model supports obstacles as two-dimensional objects, for which data elements for buildings are readily available from sources such as OSM [23] and is sufficient for the ground-based geometric perspective of vehicles with antenna heights that do not vary significantly from one another. However, the entire process to gather real-world buildings data and produce it in the required format may improve with an additional standalone ns-3 utility. Additionally, the Topology
class could be extended to manage obstacles other than buildings (e.g., other vehicles, foliage, hills and crests, etc.) for which data sources could be identified. Furthermore, the obstacle model may benefit from extension to 3D, which can be easily implemented, although an appropriate source of 3D coordinate information would need to be explored (i.e., as OSM only provides 2D data for obstacles).

Third, in addition to WiFi, the obstacle model could be utilized for other wireless models in ns-3 (e.g., LTE, LR-WPAN, and WiMax) and could potentially replace the current buildings model, which limits buildings to cubes with linearly placed x- and y-coordinates and is implemented mainly for LTE modeling only. Nonetheless, the specific requirements of loss models suitable for other wireless models would need to be extensively validated to determine their interactions with obstacle boundaries and/or interiors. For example, propagation loss for some wireless models may not depend as much on obstacle interior traversals, but instead on reflections from edges due to cornering effects. Regardless, many geometric-based concepts would likely be found to be in common (e.g., obstacle boundaries as 2D/3D objects, obstacle collections in topologies, common geometric tests such as: intersection, interior, area, volume, etc.). Such common geometric concepts may benefit from a designated core ns-3 module (e.g. topology, or buildings) dependent upon a shared library, such as CGAL.

7. REFERENCES


